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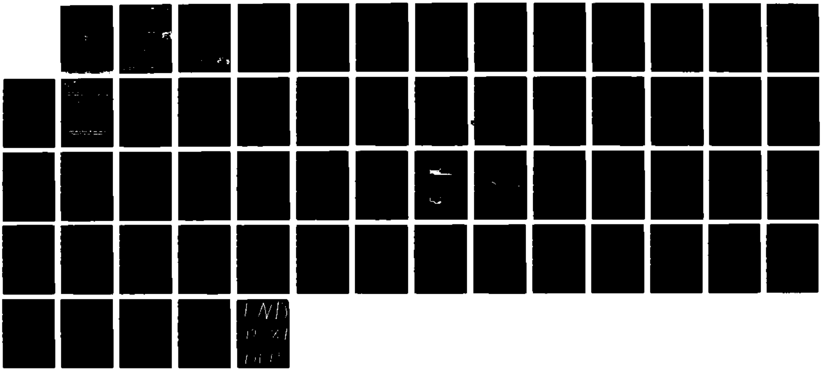

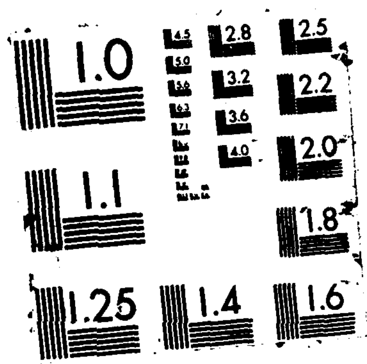
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Performance-Limiting Factors in MPD Thrusters

Final Report for the period 12/15/84 - 4/30/86
on Grant AFOSR-83-0035-C
Attn: Dr. Julian Tishkoff, AFOSR/NA
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By: Manuel Martinez-Sanchez, Associate Professor
MIT, Dept. of Aeronautics/Astronautics

4/6/87

Abstract

The work reported here, for the period 12/5/84 through 4/30/86, produced the following results:

(a) A theoretical formulation of the flow of plasma in a variable area accelerator under conditions where the voltage is dominated by the back e.m.f., showing novel features akin to those found in ordinary gas dynamics, but with the magnetoacoustic speed playing the controlling role.

(b) A numerical model of an axisymmetric MPD thruster of realistic geometry with fully coupled gas and electrodynamic effects, but limited by numerical difficulties to conditions well below onset.

(c) Design and construction of test channels to investigate the effects predicted by the above theories, and

(d) Generation of a limited computerized MPD data base.

1. Introduction. Research Objectives

Our work statement for the third year of our AFOSR Grant, covering the period of Dec. 15, 1984 to Dec. 14, 1985 (later extended to April 30, 1986) included three broadly defined tasks:

(a) Analytical study of simplified models of the flow and current attachment in MPD channels, with emphasis on the low density regions of the lip anode and the plume.

(b) Development of a 2-D axisymmetric numerical model for calculation of the steady state flow and electrodynamics of realistic MPD thruster configurations.

(c) Experimental testing of theoretical predictions on MIT designed thrusters to be operated at the R&D Associates facility in Alexandria, Virginia.

During the year, a fourth task was added, to construct a Personal Computer based Data Base of MPD data and design information.

In the following sections we give an overview of the accomplishments in these tasks, making reference to several Appendices, where additional details are contained.

2. Outline of Work Accomplished

Early in our efforts to develop an understanding of the way current distributes itself in an MPD thruster, and the way mass tends to migrate towards the central cathode and leave partially depleted anodic regions behind, it became apparent that the role of magnetic convection as a dominant effect in the MPD regime, while implicitly acknowledged in previous work, had not been properly appreciated, nor had the simplifications afforded by this dominance been adequately explored before. In essence, this indicated the desirability of examining the high Magnetic Reynolds Number regime, which, together

with the dominance of magnetic over gas pressure, can be said to define the specific MPD realm. The practical value of this Magnetic Reynolds Number, Rm, is of the order of 3 to 10, which is only moderately high, but the clarifying insights afforded by the high Rm limit are still expected to be quite useful in steering future research and design work.

A first result of this redirection of our analytical work was the AIAA paper included here as Appendix 1. In it we first show how the $Rm \rightarrow \infty$ limit reduces the plasma dynamics to a form familiar from ideal gas dynamics, since magnetic pressure is found to be governed by density alone. We thus are led naturally to concepts such as choking (but at the Alfven velocity instead of the speed of sound), convergent-divergent accelerators, with the lofting being dictated by the desired current distribution, and anode lip current concentrations as a form of Prandtl-Meyer expansion fans. Further, to explore the two-dimenional effects induced by Hall currents, we then introduce perturbations of density and other properties superimposed on a one-dimensional flow. This 1-D flow was assumed to be achieved by application of a properly selected axial electric field distribution, which, when relaxed to zero, introduces a non-zero Hall current and two-dimensional effects. The usefulness of this perturbation approach is limited to conditions not too close to "onset", but as the results contained in our 2nd yearly report show, the strong nonuniformities are likely to appear only at currents upwards of 90% of onset. It must be noted that the basic flow upon which the expansion is based satisfies the condition $E-uB \ll E$, which is strictly true at $Rm \rightarrow \infty$. For finite Rm, the inequality

applies well only far from the inlet and exit current concentrations, as our later work has clarified. However, the convergent-divergent design adopted also implies very weakened inlet and outlet concentrations, which make the results reported in Appendix 1 applicable even at only moderate Rm values.

The concepts discussed above are quite novel, and were met with some resistance. Particular concerns were raised by Drs. King and Lawless about the validity of the Alfven (or, more generally, magnetosonic) choking conditions since it was their opinion that classical <u>sonic</u> choking was mainly responsible for the greater part of the performance parameters (voltage, in particular) of MPD thrusters. Dr. Turchi also questioned the applicability of $Rm \to \infty$ concepts at the realistic values found in practice.

We have investigated the problem in more detail since then, and by the close of the reporting period had achieved substantial clarification of these issues. A paper is in preparation for the 1987 Electric Propulsion Conference that will go in considerable detail over the mathematical structure of the self-field accelerated plasma problem: an outline is included here as Appendix 2. The essential result is that the channel voltage is, in fact, largely determined by the magnetoacoustic (downstream) condition and that the role of classical sonic choking, which is indeed present in the problem, is limited to determining the inlet flow velocity and density.

This then throws into question any explanation of the onset phenomena as resulting from the inability of the channel voltage (if prescribed by upstream conditions) to exceed everywhere the back e.m.f., since, in fact, it is this maximum back e.m.f. that determines the voltage for given channel length, current and geometry. As to the applicability of high Rm concepts, the answer is less complete, but both analysis and numerical work suggest that 10% accuracy in, for instance, voltage, can be obtained with the $Rm \to \infty$ limit if properly used when $Rm > 10$.

The second of the tasks for the year was the development of a numerical code for realistic geometries of MPD devices. Progress here has been steady but slower than anticipated, due to the difficulty of the problem. Some of the difficulty is clearly highlighted by the one-dimensional results just discussed: for instance, as Appendix 2 shows, the sonic passage condition imposes very large inlet density gradients, even though this has only a small downstream effect. These gradients will be very difficult to resolve in a 2-D grid, but if their nature is understood, we can hope to incorporate their effects in a manner analogous to that used for shocks or sheath drops. Also difficult is the development of numerical schemes robust enough to handle the very low density (and therefore high Hall parameter) regions which appear near the anode of the thruster. These regions

require careful numerical handling to avoid appearance of negative densities and other non-physical effects which lead to computational instability. More generally, there is a general lack of analytical guidance on the stability properties of the usual CFD methods when extended to our more complicated situation.

These problems notwithstanding, we have developed a first-generation code documented in Mr. Chanty's Master's Thesis (Ref. 1), which has produced meaningful results for a simple axisymmetric channel with 6 g/sec of Argon at currents up to 10 KA. Convergence difficulties did not allow higher currents to be included in this fully-coupled model. On the other hand, separate computations of flow or current distributions (with one or the other kept frozen) can be routinely made with the code. More recent work has refined these results by including more spatial resolution, smoothing the grid and improving the iteration method. We have acquired, with AFOSR funding, a 20% share in a multi-processor vector computer, and plan to move our VAX codes to it, with order-of-magnitude increases in speed and storage. Appendix 3 shows some of the results of the work in Ref. 1.

Turning to the area of experimental verification, an experiment has been designed and built to test several predictions of plasma-dynamic theories which have been presented elsewhere (see Appendix 1). These theoretical results indicate that area contouring can be used to modify significantly the performance of MPD thrusters, and, in particular, that convergent-divergent area distributions can be devised to produce a nearly uniform current distribution, which should

result in reduced frozen losses. Other aspects of the theory to be experimentally tested include the existence of magnetosonic choking at the channel throat and the approximate similarity of the magnetized plasma flow to that of an ordinary gas with a specific heat ratio of 2.

Two thrusters have been designed for these purposes, one with a constant area and the other with a variable area (equal at the throat to that of the first thruster). The approximate two-dimensional theory of Appendix 1 was used to design this second channel for a specified, near-constant current density. The channels are show in Fig. 1. Design conditions are 4.25 g/sec (Argon) and 26 KA, which are well below the onset conditions predicted by anode starvation theory. Gas injection is through four rows of 12 choked holes each, with six fast valves feeding the plenum.

The experimental facility for the tests is located at the Washington Laboratory of RDA Associates, under an AFOSR funded cooperative arrangement with MIT. An existing facility has been upgraded over the last year, to provide current pulses of 1 msec at 50 KA with background pressure below 10 Torr. Diagnostics include terminal characteristics and electric and magnetic probe data, acquired using high speed Le Croy digitzers, plus exit-plane optical observations of plasma density and velocity and species temperatures using a 1.26 m Spex spectrometer with 0.02 A resolution and both PM tubes and a Silicon Intensified Target digitizing camera.

Testing is currently underway on these channels, and results will be reported at the 1987 Electric Propulsion Meeting.

Concurrent with the preceding investigations, we have undertaken the construction of a data base for MPD technology and science, with the objective of (a) providing easy access to basic data and results in the field; (b) creating a manageable structure onto which future results can be inserted, and (c) facilitating and, to the extent possible, performing cross-correlations and comparisons of data and results from various sources and viewpoints . We have so far collected and catalogued a moderately large number of publications and reports (Appendix 4), which have been entered into a computerized file in D-Base 3 (an Ashton-Tate trademark), using an IBM PC-AT computer. This data base is being expanded in three directions, namely, by entering additional reports, by increasing the number of access modes, and by increasing the amount of information per publication. Currently, the base can be entered by author, date, laboratory or title. Our next planned additions include a list of technical keywords to be scanned, selected to cover the MPD field, and the inclusion of a brief abstract with the paper listing.

At the same time, we are in the process of scanning the papers now in the data base and abstracting our selection of important technical results from each of them. This is clearly the most complete form of the eventual data base, and we face the challenge of incorporating such extended information as tables and graphs into the computerized data base, or, more likely, of cross-referencing between it and a paper-copy supplement containing such data. In either case, the data must be classified by topic rather than by source, which poses an additional challenge. Also, as we approach commpletion of the published material, we must dig into unpublished data or reports in the possession of various laboratories.

3. Personnel Associated with this Research

The work was directed by Associate Professor Manuel Martinez-Sanchez, with the cooperation of research assistants D. Heimerdinger (Doctoral Candidate), J. Marc Chanty (M.S., Sept. 1986; currently a Doctoral Candidate), and Tze-Wing Poon (M.S., Sept. 1985).

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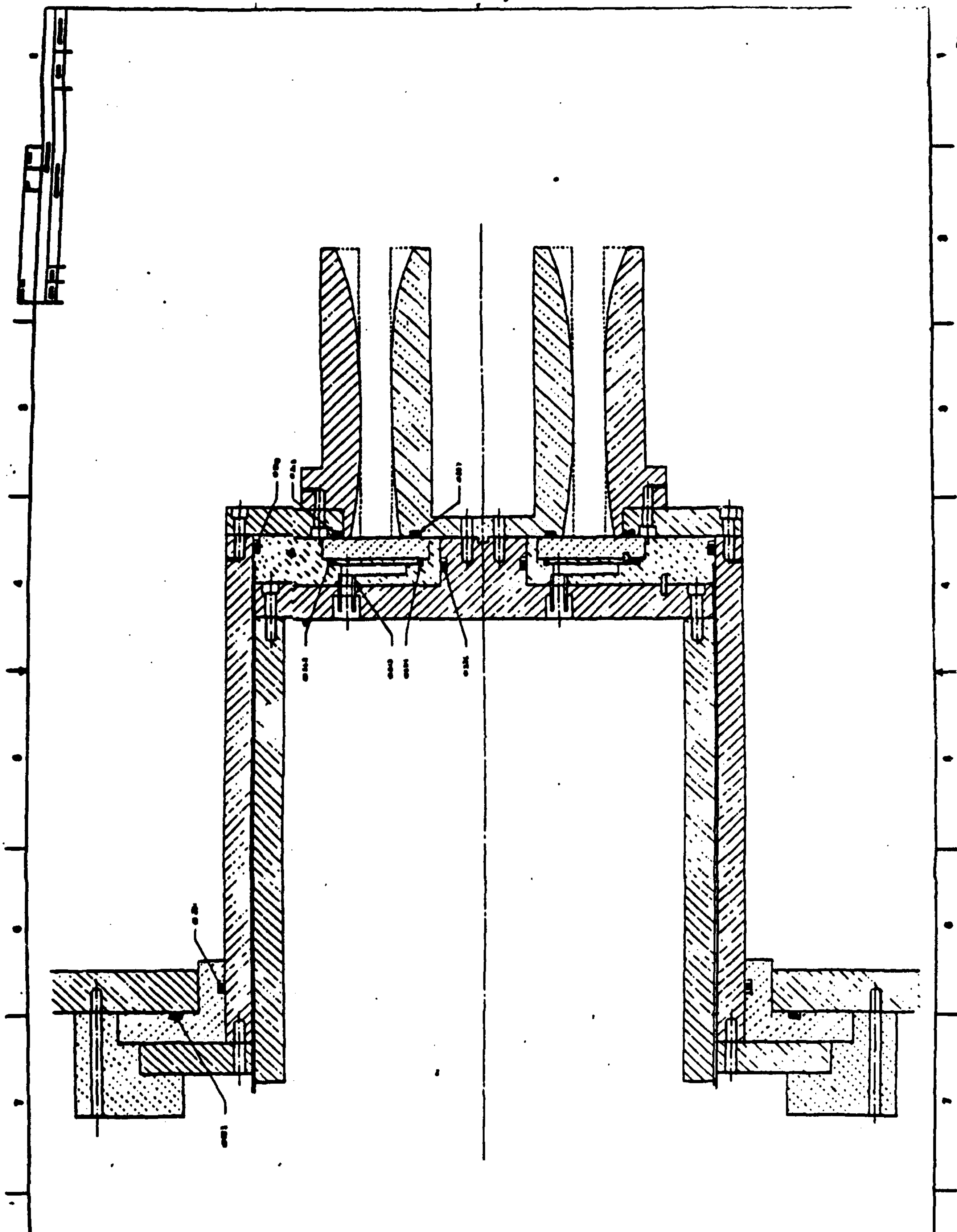

Fig. 1. The constant and variable area MPD thrusters and supporting structure

APPENDIX 1

AIAA'85

AIAA-85-2040

Two-Dimensional Analysis of an MPD Arcjet

M. Martinez-Sanchez and D. Heimerdinger,
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AIAA/DGLR/JSASS 18th International Electric Propulsion Conference

September 30-October 2, 1985
Alexandria, Virginia

TWO-DIMENSIONAL ANALYSIS OF AN MPD ARCJET

M. Martinez-Sanchez* and D. Heimerdinger**
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Abstract

A theory is presented of the flow of a fully ionized plasma in an MPD accelerator. Examination of the High Magnetic Reynolds number limit reveals the origin of the anode-lip and cathode-end current concentrations and shows that a redistribution of current can be effected by contouring the channel. More generally, there exists a distribution of electrode potentials for which current is purely transverse. Achieving this condition would require electrode segmentation, but would eliminate anode depletion as a cause of onset. A linearized analysis is presented for cases with other electrode potential distributions, using the transverse case as a zero'th order approximation. The results show that strong transverse mass redistribution can be brought about by even minor axial currents. The theory yields a simplified onset criterion similar to that of Baksht, and can also be used to guide the design of MPD channels with desired current and mass distributions.

Nomenclature

A_n	expansion constants (Eq. 52)
a	constant (Eq. 34)
$\mathbf{B}$	magnetic induction
B_n	expansion constants (Eq. 53)
B_0	magnetic induction at x=0
b	constant (Eq. 34)
C_n	Fourier coefficients
c	constant (Eq. 1)
$\mathbf{E}$	electric field
e	fundamental charge; also a constant (Eq. 37)
G	total stream function
g	constant (Eq. 40)
h	channel height
h'	perturbation channel height
I	total current
$\mathbf{i}_z$	unit vector in z direction
$\mathbf{j}$	current density
K_n	constants (Eq. 45)
L	channel length
M	molecular weight
$\dot{m}$	mass flow rate
m_i	ionic mass
n	integral index
P	gas pressure
$\bar{R}$	constant (Eq. 24)
R_g	specific gas constant
R_m	magnetic Reynolds number
$R_{1,2}$	constants (Eq. 50)
$\mathcal{R}$	universal gas constant
r	constant (Eq. 36)
$r_{-1,-2}$	decay constants (Eq. 43)
$r^{1}_{-1,-2}$	constants (Eq. 52)
s	magnetoacoustic velocity
T	plasma temperature
$\mathbf{u}$	vector velocity
u	velocity in the x direction
v	velocity in the y direction
w	channel depth
x	axial coordinate
y	transverse coordinate
β	Hall parameter
$\bar{\beta}$	constant (Eq. 24)
Γ	mass flux
γ	specific heat ratio; also a constant (Eq. 54)
η	non-dimensionalized density
λ_n	eigenvalues
μ	sheath constant (Eq. 35)
μ_0	permeability of free space
ξ	non-dimensionalized mass flux
π	total pressure
ρ	gas density
σ	conductivity
τ	inverse interaction number
Ψ	stream function
$\langle\,\rangle$	transverse average

subscripts:

c, a	at the cathode or anode
n	integral index
ref	reference quantity
x, y	in the x or y direction

superscripts:

$\circ$	zero'th order
$'$	non-dimensional quantity; also used as perturbation (Eqs. 31 and 42); or as a name "tag" (Eq.52)
$*$	choking condition

* Associate Professor, Department of Aeronautics and Astronautics
** Graduate Student, Member AIAA

Introduction

The goals of the designer of an MPD thruster are to obtain a desirable overall performance, plus desirable internal distributions of electrode current densities, ohmic dissipation, and possibly gas density or mass flux. Purely electrodynamic considerations can provide valuable information for overall performance (e.g., the Maecker thrust equation), but the strong electromechanical coupling must be considered in order to achieve the goals related to internal flow and current distributions. This coupling can affect performance in several important ways such as in the establishment of the onset limitation or in the determination of lifetime or materials choice (from local

electrode loadings). In this paper, we apply a simple single fluid model of the MPD plasmadynamics to the problem of designing a two-dimensional plasma accelerator for prescribed distributions of flow and current. The analysis provides insight into the behavior of the device and gives guidelines on the choice and shapes of the parameters for specific design goals. While the trends and limits obtained are believed to be of general usefulness, their accuracy is limited by the relative crudity of the plasma model.

Model Formulation

The plasma is modelled as a fully ionized gas characterized by a constant electrical conductivity σ, and a Hall parameter β which is proportional to the magnetic induction B and inversely proportional to the gas density ρ:

$$\sigma = \text{Constant} \; ; \quad \beta = c \frac{B}{\rho} \quad (c = \frac{\sigma m_i}{e}) \tag{1}$$

The gas is assumed to follow the ideal gas law $P = \rho R_g T$, with constant molecular mass and temperature where R_g is calculated considering an electron-ion fluid. This last approximation is partially justifiable on the basis of the large electron thermal conductivity and the large available reservoir of ionization and excitation energy, but it is ultimately just a convenient device to facilitate the analysis.

The generalized Ohm's law is used in the form

$$\sigma(\mathbf{E} + \mathbf{u} \times \mathbf{B}) = \mathbf{j} + \mathbf{j} \times \boldsymbol{\beta} \tag{2}$$

where $\boldsymbol{\beta} = \beta(\mathbf{B}/B)$. The electron pressure gradient term is neglected because Baksht et al. (Reference 1) included this effect in their simplified analysis and found that the results were minimally modified, with no effect on the overall behavior. The ion slip is also neglected, due to the fact that the electron Hall parameter rarely exceeds values of the order of unity in MPD channels.

Continuity, momentum, and the pertinent Maxwell's equations are listed below:

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \tag{3}$$

$$\rho(\mathbf{u}\cdot\nabla)\mathbf{u} = -\nabla\left(p + \frac{B^2}{2\mu_e}\right) \tag{4}$$

$$\mathbf{j} = \nabla \times \frac{\mathbf{B}}{\mu_e} \; ; \qquad \mathbf{B} = B\, \mathbf{i}_z \tag{5}$$

$$\nabla \times \mathbf{E} = 0 \tag{6}$$

$\mathbf{E}$ and $\mathbf{j}$ can be eliminated and an induction equation formed

$$\frac{\partial^2 B}{\partial x^2} + \frac{\partial^2 B}{\partial y^2} + \left[\frac{\partial B}{\partial y}\frac{\partial \beta}{\partial x} - \frac{\partial B}{\partial x}\frac{\partial \beta}{\partial y} \right] =$$

$$= \mu_e \sigma \rho \mathbf{u}\cdot\nabla \left[\frac{B}{\rho} \right] - \mu_e \sigma \nabla\cdot(\mathbf{u}B) \tag{7}$$

where the Laplacian terms represent the magnetic diffusion, the third term arises from the variations of the Hall parameter due to its inverse dependence on gas density, and the right hand side represents the effect due to magnetic convection.

It is useful to non-dimensionalize these equations using reference quantities representative of those encountered in MPD channel flow. Imposition of continuity and momentum-like constraints ($\rho_{ref} u_{ref} h^* = G$ and $\rho_{ref} u_{ref}^2 = B_e^2/\mu_e$) provides for these meaningful reference parameters. This results in the non-dimensional variables

$$x' = \frac{x}{L} \qquad y' = \frac{y}{h^*} \qquad v' = \frac{vL}{u_{ref} h^*}$$

$$u' = \frac{u}{u_{ref}} \qquad \rho' = \frac{\rho}{\rho_{ref}} \qquad B' = \frac{B}{B_e} \tag{8}$$

and the non-dimensional equations

$$\frac{\partial(\rho' u')}{\partial x'} + \frac{\partial(\rho' v')}{\partial y'} = 0 \tag{9}$$

$$\rho'(\mathbf{u}'\cdot\nabla)u' = -\frac{\partial}{\partial x'}\left(r\rho' + \frac{B'^2}{2}\right) \tag{10}$$

$$\rho'(\mathbf{u}'\cdot\nabla)v' = -\frac{\partial}{\partial y'}\left(r\rho' + \frac{B'^2}{2}\right) \tag{11}$$

$$\left[\frac{h^*}{L}\right] \frac{\partial^2 B'}{\partial x'^2} + \frac{\partial^2 B'}{\partial y'^2} + \left[\beta_{ref} \frac{h^*}{L}\right]\left[\frac{\partial B'}{\partial y'}\frac{\partial \beta'}{\partial x'} - \right.$$

$$\left. - \frac{\partial B'}{\partial x'}\frac{\partial \beta'}{\partial y'}\right] = \left[R_m \frac{h^*}{L}\right] \rho' \mathbf{u}'\cdot\nabla \left[\frac{B'}{\rho'}\right] \tag{12}$$

The following dimensionless parameters appear:

$$\frac{h^*}{L} = \text{channel aspect ratio} \tag{13}$$

$$\beta_{ref} = c\frac{B_e}{\rho_{ref}} = \frac{\sigma m_i}{e}\frac{B_e^3 h^{*2}}{\mu_e G^2} \tag{14}$$

$$R_m = \mu_e \sigma u_{ref} h^* = \frac{\sigma B_e^2 h^{*2}}{G} \tag{15}$$

$$r = \frac{R_g T \rho_{ref}}{B_e^2/\mu_e} = \frac{R_g T \mu_e^2 G^2}{B_e^4 h^{*2}} \tag{16}$$

The High Magnetic Reynolds Number Limit

Even though R_m is not likely to be really large in MPD channels, it is large enough that some information on the flow behavior can be gained by considering first the limit $R_m \gg 1$.

From this point on we will drop the (') to denote dimensionless quantities. As $R_m \to \infty$ and $v \to 0$, B/ρ becomes a convective constant. The effective total pressure is now

$$\pi = r\rho + \frac{1}{2}\left[\frac{B}{\rho}\right]^2 \rho^2 \tag{17}$$

and is a function of density alone. Being barotropic means that a Bernoulli-type conservation equation can be obtained:

$$u \cdot \nabla \left[\frac{u^2}{2} + \tau \ln \rho + \left[\frac{B}{\rho} \right]^2 \rho \right] = 0 \qquad (18)$$

showing that the quantity in brackets is another convective constant.

In this limit, the general behavior of the plasma flow can therefore be described as being a direct analog of an ordinary compressible flow with the particular pressure-density variation π, which, if $\tau << 1$ is nearly that for a specific heat ratio $\gamma = 2$. If the convective constants are constant across streamlines then all the familiar properties of two-dimensional ideal gas flows then have their counter-part as high Magnetic Reynolds number flows: choking, Prandtl-Meyer expansions, shocks, etc. The role of the speed of sound is here played by the disturbance speed

$$s = \sqrt{\frac{d\pi}{d\rho}} = \sqrt{\tau + \frac{B^2}{\rho}} \qquad (19)$$

which is the magneto-acoustic velocity and reduces to the speed of sound at zero magnetic field and to the Alfven speed for low pressure and high field.

Two important identifications can be made in these flows:

(a) Iso density lines are also iso field lines, hence they are electric current lines.

(b) Streamlines are also equipotentials.

Consider a crude model of an MPD channel consisting of a rectangular channel discharging into a vacuum where $B=0$ (Fig. 1). Since the constant-area section discharges into a vacuum, it must be a region of critical flow ($u = s$). From the Bernoulli integral (Eq. 18), the magneto-acoustic speed (Eq. 19), and the assumptions $\tau<<1$ and $u(0)=0$, $u=s=((2/3)/\rho_e)^{1/2}$ which is $(2/3)^{1/2}$ times the stagnation Alfven velocity. Also $B = 2/3$ ($B(0) = 1$) and $\rho = (2/3)\rho(0)$. The flow must make an abrupt transition from ρ_e to $(2/3)\rho_e$ as it accelerates rapidly to the critical speed and the corresponding fall of B implies a concentrated current sheet.

The expansion into vacuum proceeds by way of a pattern of lip-centered expansion fans which interact mutually downstream to form a supercritical jet. The expansion fans also represent current concentrations. Fully 2/3 of the total current is carried by these pseudo arcs, and the current pattern in the jet can be predicted by the well established method of characteristics. For $\tau << 1$, a simple calculation gives for the limiting streamline (and also the limiting Mach-Alfven line) an inclination of $(\sqrt{3} - 1)/2$ radians, or 65.8° (Fig. 2).

If a convergent-divergent nozzle were provided, the "chamber" flow would be subcritical, since the critical, or magneto-acoustic speed is reached exactly at the throat and the exit flow will now be super-critical. The initial jump in B is now decreased and the exit lip current concentration is also weakened. The remaining current is smoothly distributed along the nozzle with current lines corresponding to constant-ρ lines.

The Slender Channel Approximation

We wish to examine the flow in cases with more realistic parameters, with emphasis on providing a smooth expansion that may yield a more benign current distribution. We will exploit the slenderness of the likely geometries by assuming that $h^*/L << 1$.

It is convenient to use as the transverse independent variable the stream function Ψ, defined by

$$\rho u = \frac{\partial \Psi}{\partial y} \qquad \rho v = -\frac{\partial \Psi}{\partial x} \qquad (20)$$

where Ψ is nondimensionalized by G. The governing equations reduce to

$$\bar{R} \left[\frac{\partial (B/\rho)}{\partial x} \right] = \frac{\partial}{\partial \Psi}\left[\rho u \frac{\partial B}{\partial \Psi} - \frac{\bar{\beta}}{\rho} \frac{d\pi}{dx} \right] \qquad (21)$$

$$\rho u \left[\frac{\partial u}{\partial x} \right]_\Psi + \frac{d\pi}{dx} = 0 \qquad (22)$$

$$\tau \rho + \frac{B^2}{2} = \pi(x) \qquad (23)$$

$$\text{where } \bar{R} = R_m \frac{h^*}{L} \text{ and } \bar{\beta} = \beta_{ref} \frac{h^*}{L}. \qquad (24)$$

To impose the electrode wall boundary conditions, Ohm's law is solved for the axial field, E_x, (normalized by $u_{ref}B_e$) resulting in

$$R_m E_x = \rho u \frac{\partial B}{\partial \Psi} - \bar{\beta} \frac{B}{\rho} \left[\frac{\partial B}{\partial x} \right]_\Psi \qquad (25)$$

The implication of Eq. (25) is that the transverse Lorentz forces due to any axial current are hydrostatically balanced by a lateral pressure gradient.

Design for Zero Axial Current

There is interest in eliminating the axial current due to the Hall effect which has been related to anode starvation and onset (Ref 1). Examination of Eqs. (21)-(23) shows that solutions do exist in which all the variables depend on x alone. Again, two convective constants are found and explicit solutions can be found given initial values of ρ, B, and an axial pressure specification of $\pi(x)$. These expressions are

$$\rho = \frac{\sqrt{\tau^2 + 2(B/\rho)^2 \pi(x)} - \tau}{(B/\rho)^2} \qquad (26)$$

$$\frac{B}{\rho} = \frac{1}{\rho(0)} \; ; \quad B = \left[\frac{B}{\rho} \right] \rho \; ; \quad h = \frac{1}{\rho u} \qquad (27)$$

$$u = \sqrt{u(0)^2 + 2\tau \ln \frac{\rho(0)}{\rho} + 2(B/\rho)^2(\rho(0) - \rho)} \qquad (28)$$

At the "choking point", the local density ρ^* is given by the solution to the equation $u = s$, or

$$\frac{\rho^*}{\rho(0)} = \frac{2}{3} - \frac{r}{3\rho(0)} \left[1 - \frac{\rho^{*2}}{\rho(0)^2} \ln \frac{\rho(0)}{\rho^*} \right] + \frac{\rho^{*2}}{\rho(0)} u(0)^2 \qquad (29)$$

The height distribution is shown in Fig. 4 as a function of $B/B(0)$ for $r = 0$. For the particular case when a constant current density is desired, the curve shows the true shape of the channel.

The price that must be paid for the achievement of a purely transverse current is the required presence of an axial electric field. Its value follows from Eq. (25):

$$E_x = - \frac{\bar{\beta}}{\bar{R}_M} \left[\frac{B}{\rho} \right] \frac{dB}{dx} \qquad (30)$$

This implies the imposition of an axial field through a segmented channel with independent control of the voltage of each segment.

Linearized Analysis for Non-Zero Axial Current

1. Formulation:

When the axial field departs from the value given by Eq. (30), axial currents and, consequently, lateral density gradients, will appear in the plasma. A particular example is that of a channel with continuous metallic walls; if the axial variations of the electrode voltage drops can be neglected in comparison to the Hall field of Eq. (30), then E_x will be zero along the walls, and j_x will be nonzero. When the voltage drop variations are accounted for, E_x will not be precisely zero, but will not generally agree with Eq. (30) either.

We will assume relatively small departures from the purely transverse condition where E_x is given by Eq. (30). The quantities corresponding to this zero'th order solution will be denoted by a zero superscript, and the equations will be linearized in the nondimensional perturbation quantities, defined by

$$\rho = \rho^\circ(1 + \eta) \; ; \quad \Gamma = \rho u = \Gamma^\circ(1 + \zeta)$$
$$B = B^\circ + B' \qquad (31)$$

but with no perturbation in π. In addition, the channel profile is to be perturbed to accomodate the ρu perturbations brought on by the E_x variations.

Performing the linearization of Eqs. (21)and (25) gives new perturbation induction and electric field equations

$$- \bar{R} \left[\frac{B}{\rho} \right]^\circ \frac{\partial \eta}{\partial x} = r\Gamma^\circ \left[\frac{\rho}{B} \right]^\circ \frac{\partial^2 \eta}{\partial \psi^2} - \frac{\bar{\beta}}{B^\circ} \left[\frac{B}{\rho} \right]^\circ \frac{d\pi}{dx} \frac{\partial \eta}{\partial \psi} \qquad (32)$$

$$R_M E_x = - r\Gamma^\circ \left[\frac{\rho}{B} \right]^\circ \frac{\partial \eta}{\partial \psi} + r \bar{\beta} \frac{\partial \eta}{\partial x} + \bar{\beta} \left[\frac{B}{\rho} \right]^\circ \frac{dB^\circ}{dx} \eta \qquad (33)$$

The coefficients in Eq. (32) and (33) are functions of x alone, and, in fact, B°/ρ° is a pure constant equivalent to $(B/\rho)^\circ$. The factor $(d\pi/dx)/B^\circ$ would be nearly constant in a constant-current zero'th order channel, and Γ° is flat in the throat region becoming small as the channel diverges. Thus we are justified in adopting, for an approximate solution, the <u>axially averaged</u> values of the coefficients; Eq. (32) will be written as

$$\frac{\partial \eta}{\partial x} = a \frac{\partial^2 \eta}{\partial \psi^2} + b \frac{\partial \eta}{\partial \psi} \qquad (34)$$

where a and b are constants given by

$$a = \frac{r \langle \Gamma^\circ \rangle}{\bar{R}(B/\rho)^{\circ 2}} \; ; \quad b = \frac{\bar{\beta}}{\bar{R}} \langle \frac{1}{B^\circ} \left[- \frac{d\pi}{dx} \right] \rangle ; \qquad (35)$$

the symbol $\langle \; \rangle$ indicates axial averaging.

For analysis, we will assume that the perturbation E_x' of E_x on the electrode walls is a prescribed fraction $(-\mu)$ of the zero'th order value, so that

$$r \frac{\partial \eta}{\partial \psi} - \frac{\partial \eta}{\partial x} + e\eta = \mu e \qquad (\text{at } \psi = 0, 1) \qquad (36)$$

where

$$r = \frac{\langle \Gamma^\circ \rangle}{\bar{\beta} \, (B/\rho)^\circ} \qquad (37)$$

and

$$e = \frac{(B/\rho)^\circ}{r} \langle - \frac{dB^\circ}{dx} \rangle \qquad (38)$$

The precise value of μ must be obtained from a model of the sheaths on the electrode walls. If we assume metallic walls with constant voltage drops so that the total E_x is zero at the walls, we must use $\mu = +1$. This is the only case we have so far analyzed.

In adopting the slender channel assumption, all diffusion terms were neglected transforming the problem from elliptic to parabolic. Therefore an extra condition on η $(\eta(x=0,\psi))$ must be prescribed but no condition can be imposed on downstream boundary conditions.

In a mathematical sense, we are solving only the <u>outer</u> limit of a singular perturbation problem with the small parameter $(h^*/L)^2$. The inner-outer matching requires the elimination of the exponentially growing parts of the outer solution. We have investigated the question of whether a similar inner-outer matching is required near the $x = 0$ end, i.e., whether our "outer" solution can be made to fit the initial conditions or, on the contrary, a near-discontinuity may appear at $x = 0$. The results of this analysis indicate that no "boundary layer" is forced at $x = 0$ on the zero'th order solution as long as <u>no axial current</u> is allowed. Otherwise the diffusion term,

$\partial^2\eta/\partial x^2$, cannot be neglected. Notice that the absence of a strong transition at $x = 0$ is not a universal result: in fact, it was previously seen that one such singular layer does appear when the area distribution, instead of the total pressure distribution, is prescribed.

To complete the linearized formulation, the perturbation on the mass flux, Eq. (22) is calculated:

$$\frac{\partial\xi}{\partial x} + 2\,\frac{d\ln u^o}{dx}\,\xi = \frac{\partial\eta}{\partial x} + \frac{d\ln u^o}{dx}\,\eta \qquad (39)$$

which integrates to

$$\xi(x,\Psi) = \xi(0,\Psi) + \eta - \eta(0,\Psi) - \frac{g}{u^{o2}}\int_0^x \eta\,dx \qquad (40)$$

$$\text{with}\quad g = \left(-\frac{1}{\rho^o}\frac{d\pi}{dx}\right) \frac{\bar R}{\bar\beta}\left[\frac{B}{\rho}\right]^o b \qquad (41)$$

The channel height follows from the integration of the stream function; the zero'th order value is $h^o = 1/\Gamma^o$, and its perturbation is given by

$$\frac{h'(x)}{h^o(x)} = -\int_0^1 \xi\,d\Psi = -\bar\xi = \overline{\xi(0,\Psi)} + \bar\eta - \overline{\eta(0,\xi)} - \frac{g}{u^{o2}}\int_0^x \bar\eta\,dx \qquad (42)$$

where the overbar indicates transverse averaging.

2. Solution of the Linearized Equations

The solution to the above equations for the case of equipotential walls (μ=1 in Eq. (36)) is presented. Using the method of separation of variables, and taking special care to accomodate the presence of axial derivatives $\partial\eta/\partial x$ in the boundary conditions (Eq. (36)), we arrive at

$$\eta = 1 + C_{-1}\exp(-\lambda_{-1}x)\exp(r_{-1}\Psi) + \exp\left(-\frac{b}{2a}\Psi\right)\sum_1^\infty C_n\exp(-\lambda_n x)(\cos n\pi\Psi - K_n\sin n\pi\Psi) \qquad (43)$$

$$\text{where}\quad r_{-1,-2} = \frac{r-b \pm \sqrt{(b-r)^2+4ae}}{2a} \qquad (44)$$

$$\lambda_{-1} = (-rr_{-1}-e)\ ;\quad \lambda_{n>0} = \frac{b^2}{4a} + \pi^2 an^2 \qquad (45)$$

$$K_n = \frac{\lambda_n + e - \frac{br}{2a}}{\pi rn} \qquad (46)$$

The coefficients C_{-1}, $C_{n>0}$ must be obtained by integration performed using an initial density distribution $\eta(x=0,\Psi)$, and by satisfying a modified Fourier orthogonality condition. The initial density distribution must also be chosen so that all axially divergent terms, (in this case an additional C_{-2} term) go to zero. The simplest type of initial density profile, with zero mean, capable of satisfying this condition, is linear

$$\eta(0,\Psi) = \eta_c(2\Psi - 1) \quad\text{and} \qquad (47)$$

$$\eta_e = \left[\frac{1}{R_2} - \frac{a}{r}\right]\left[\exp(R_2) - 1\right] + \left[2\left(\frac{1}{R_2} - \frac{a}{r}\right]\exp(R_2) - \left[\frac{2}{R_2^2} - \frac{1}{R_2} + \frac{a}{r}\right]\left[\exp(R_2) - 1\right]\right] \qquad (48)$$

providing

$$C_{-1} = \frac{2rr'_{-1}}{(\exp(2r'_{-1})-1)(r-2ar'_{-1})} * \left(\left[2\left[\frac{1}{R_1} - \frac{a}{r}\right]\exp(R_1) - \left[\frac{1}{R_1^2} + \frac{1}{R_1} - \frac{a}{r}\right]\left[\exp(R_1) - 1\right]\right]\eta_c - \left[\frac{1}{R_1} - \frac{a}{r}\right]\left[\exp(R_1) - 1\right]\right) \qquad (49)$$

$$C_{n>0} = \frac{A_n - K_nB_n - \frac{2a}{r}\left[(-1)^n f(1) - f(0)\right]}{1 + K_n^2} \qquad (50)$$

$$\text{where}\quad R_{1,2} = r'_{-1,-2} + \frac{b}{2a} \qquad (51)$$

$$\text{and}\quad r'_{-1,-2} = r_{-1,-2} + \frac{b}{2a} \qquad (52)$$

$$A_n = \frac{4\eta_e}{\pi^2}\frac{1}{n^2+\gamma^2}\left[\left[\frac{n^2-\gamma^2}{n^2+\gamma^2} + \pi\gamma\right](-1)^n\exp(\pi\gamma) - \frac{n^2-\gamma^2}{n^2+\gamma^2}\right] + \frac{2(1+\eta_e)}{\pi}\frac{\gamma}{n^2+\gamma^2} * \left[1-(1)^n\exp(\pi\gamma)\right] \qquad (53)$$

$$B_n = \frac{4\eta_e}{\pi}\frac{n}{n^2+\gamma^2}\left[\left[\frac{2\gamma}{n^2+\gamma^2} - \pi\right](-1)^n\exp(\pi\gamma) - \frac{2\gamma}{n^2+\gamma^2}\right] - \frac{2(1+\eta_e)}{\pi}\frac{n}{n^2+\gamma^2} * \left[1-(-1)^n\exp(\pi\gamma)\right] \qquad (54)$$

$$\text{where}\quad \gamma = \frac{b}{2a\pi} \qquad (55)$$

3. A Numerical Example

The following example was chosen mainly for purposes of illustration and for verification of the theory. Its parameters bear some resemblance to those encountered in Argon MPD thrusters operating near onset with several grams per second of flow. We take

$R_gT = 2.496\times10^6$ J/kg $\quad B^o(0) = 0.05$ Tesla
$c = 0.00207$ kg/m³/Tesla $\quad \sigma = 5000$ mho/m

$u^*(0) = 3000$ m/s $\quad G = 0.02$ kg/sec/m

$\rho^*(0) = 1.333 \times 10^{-4}$ kg/m³ $\quad L = 0.1$ m

$$\pi = \pi(0)\left[1 - \frac{x}{0.1}\right]^2 ,$$

with x in meters.

The solution for zero axial current is presented in Figures 5 and 6 in dimensional terms.

For the purposes of the linearized solution, we adopt approximate averages as follows:

$$\langle \Gamma \rangle = 0.4 \text{ kg/sec/m}^2 \qquad \langle E_x^* \rangle = 70 \text{ V/m}$$

$$\left\langle -\frac{1}{\rho}\frac{d\pi}{dx} \right\rangle = 2.090 \times 10^8 \text{ m/sec}^2$$

With these values, the linearized equations give η expansion coefficients (Table 1) and the selected results shown in figures 7, 8, and 9. Figure 7 shows that the total density $\rho = \rho^*(1+\eta)$ is strongly concentrated near the cathode, to the point that slightly negative densities are calculated near the anode, particularly in the region near and just beyond the throat. This is a clear indication that the channel has reached onset conditions. The mass flux ρu has been assumed uniform at $x = 0$, and remains not far from uniformity, which forces the velocity to be substantially higher near the anode.

In Figure 8 we see the relatively minor transverse nonuniformity of B which is responsible for the large nonuniformities of ρ and u shown in Figure 7. The Hall parameter (which is approximately the ratio of j_x to j_y, since E_x is now near zero everywhere) is also shown in this figure, and is large, near the anode.

Figure 9 compares the unperturbed and perturbed channel contours. The differences are moderate, indicating that the average mass flux is only weakly affected by the mass redistribution.

As shown in Figure 8, B becomes zero on the cathode at about $x = 0.075$ m, while B is still positive at the anode ($B_a = 0.017$ Tesla). Assuming this is the actual channel termination point, the remaining B at the anode must drop to zero through a concentrated anode lip "quasi-arc", which carries about 34% of the total current. For comparison, truncating the channel at $x = 0.075$ m on the design with zero axial current would have left anode and cathode lip currents of about 17% of the total. Clearly, the effect of the Hall parameter has been to strengthen the anode lip concentration while unloading the cathode tip.

4. Onset Prediction

We have indicated that some looseness remains in the specification of the initial density profile $\eta(0,\hat{y})$. For comparison with the previous example, where a zero-mean, linear function was used, we use in this section an even simpler approach, which will also yield a simplified criterion for onset. To this end, we return to Eq. (43) and select $\eta(0,\hat{y})$ such as to be orthogonal (in the modified sense required by the special boundary conditions of our problem) to all the modes for $n \geq 1$. This leaves

$$\eta = 1 + C_{-1}\exp(\lambda_{-1}x)\exp(r_{-1}\hat{y}) \qquad (56)$$

and for this to have zero mean value

$$C_{-1} = \frac{-r_{-1}}{\exp(r_{-1}) - 1} \qquad (57)$$

Using the above data, $C_{-1} = -2.983$, compared to -2.661 for the linear profile.

The density at the anode root ($x = 0$, $\hat{y} = 0$) is given by

$$\frac{\rho}{\rho^*} = 2 + C_{-1} \qquad (58)$$

Equating this ratio to zero, is a simple criterion for onset since this is the first spot where the density becomes zero. Therefore $C_{-1} = -2$, or $r_{-1} = -1.593$. The quantity r_{-1} is still too complex to give any real insight. But to a crude first approximation, the (b-r) terms in Eq. (44) can be neglected, leaving $r_{-1} \approx (e/a)^{1/2}$. Accepting this gives the onset criterion $e/a = 2.54$.

From Eqs. (35) and (37), (since the nondimensional variables, like B^*, ρ^*, Γ^*, etc. are all of order unity)

$$\frac{R_m}{r^2}\frac{h^*}{L} \approx 2.54 \qquad (59)$$

Using the approximation $B_0 \approx \mu_0 I/W$ and also $G = \dot{m}/W$, we obtain

$$\frac{I^2}{\dot{m}} M^{2/5} \approx 1.2 \frac{wL^{1/5}(RT)^{2/5}}{h^{*7/5}\sigma^{1/5}\mu_0^{1/5}} \qquad (60)$$

Equation (60) displays most of the observed trends ($\dot{m}$, M, length, etc...). Aside from the numerical accuracy, this expression contains the same basic physics as that derived in Reference (1).

Conclusion

It has been shown that appropriate tayloring of the channel shape in an MPD accelerator can be used to obtain a desired axial distribution of transverse current, and that tayloring of the electrode potential distributions can be used to control and suppress axial currents and lateral density gradients. While the practical implementation of these notions may present difficulties, the theory presented can be used as a guideline for designs with perhaps better performance and longer lifetimes.

Reference

1. Baksht, F.G., Mizhes, B. Ya and Rybakov, A.B., "Critical Regime of a Plasma Accelerator," Sov. Phys. Tech. Phys., Vol. 18, No. 12, 1974.

n	A_n	K_n	C_n
- 2	- 24.332		0
1	0.4450		2.664
1	4.441	0.8683	0.9070
2	14.962	1.0834	0.0373
3	32.470	1.4437	0.0370
4	52.996	1.8402	0.00714
5	88.530	2.2513	0.00627
6	127.07	2.6696	0.00184
7	172.6H	3.0920	0.00180
8	225.17	3.5171	0.00064
9	284.7	3.9439	0.00069
10	351.3	4.3719	0.00028
11	424.9	4.8008	0.00032
12	505.5	5.2303	0.00014
13	593.1	5.6603	0.00016
14	687.7	6.0908	0.00008
15	789.3	6.5315	0.00009

Table 1: Coefficients for Eq. 43

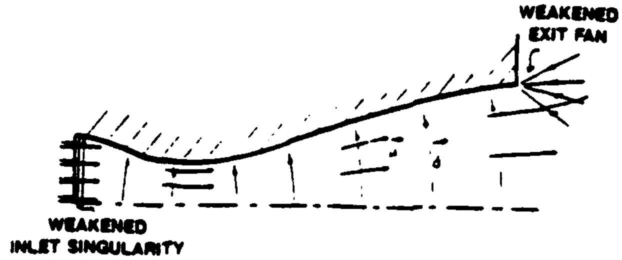

Fig. 3: Smooth Expansion and Current Distribution in Convergent - Divergent Nozzle

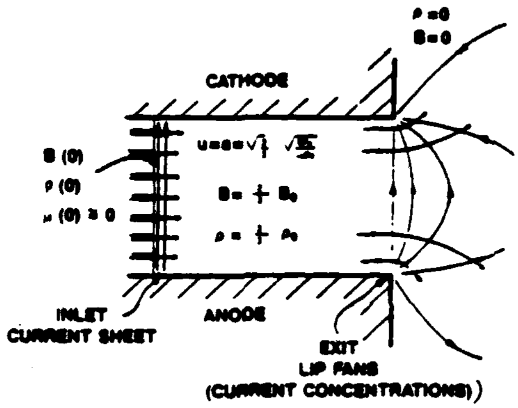

Fig. 1: Flow at $R_m \rightarrow \infty$ From Rectangular Channel

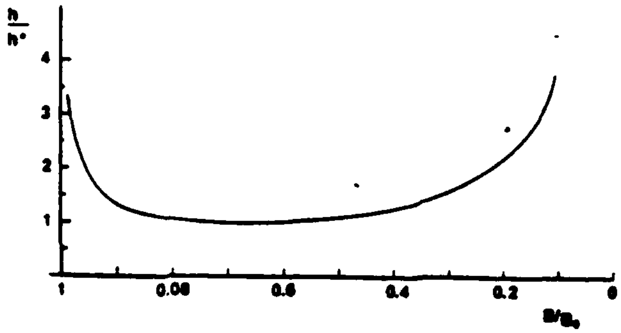

Fig. 4: Nozzle Contour for $r = 0$

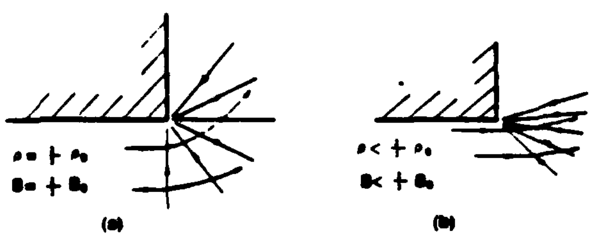

Fig. 2: Corner Expansions Into Vacuum
a. Critical Approach Speed
b. Supercritical Approach Speed

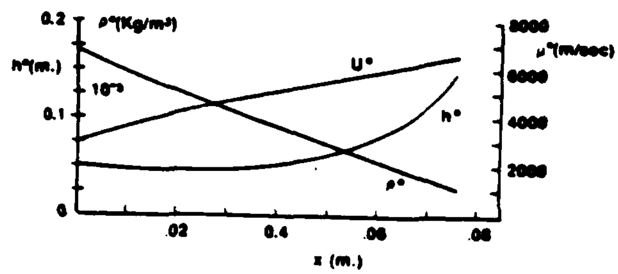

Fig. 5: Channel Height, Density, and Velocity Profiles for Zero Axial Current

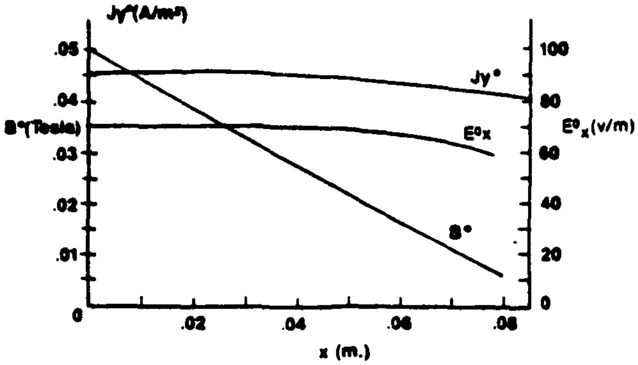

Fig. 6: Magnetic Field, Transverse Current, and Axial Field Profiles for Zero Axial Current

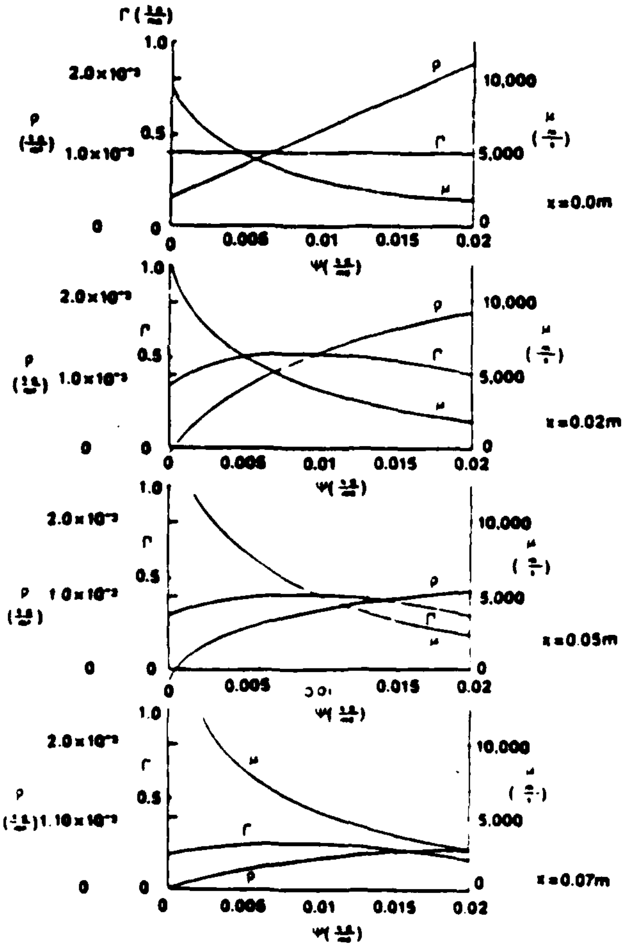

Fig. 7: Transverse Density, Velocity and Mass Flux Profiles at Several Axial Distances, for Channel with Equipotential Walls

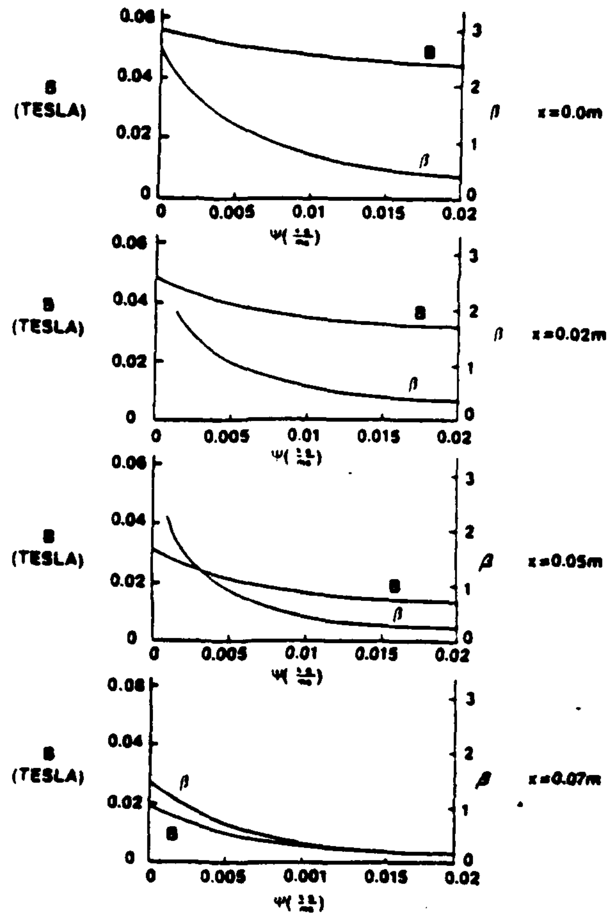

Fig. 8: Transverse Profiles of Magnetic Field and Hall Parameter at Various Axial Distances, for Channel with Equipotential Walls

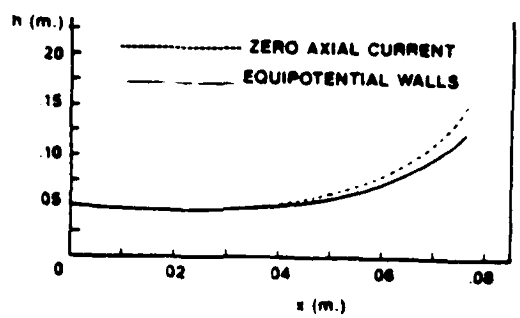

Fig. 9: Channel Height Profiles for Unperturbed ($J_x = 0$) and Perturbed ($E_{x,walls} = 0$) Cases

Reference

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APPENDIX 2

THE STRUCTURE OF SELF-FIELD ACCELERATED PLASMA FLOWS

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This paper will present a detailed analysis of the development of flow and electromagnetic properties in a contoured quasi-one-dimensional MPD channel, with a clarification of the roles of ordinary sonic passage and magnetoacoustic choking, and an assessment of the effects and potential uses of area variation.

The approach starts with the formulation of a set of governing equations incorporating the condition of zero axial current, which is required for a quasi-one-dimensional model to be consistent, and which implies a certain amount of axial electric field (although the results are also representative for axially shorted channels at conditions removed from the starved regime). Let $\dot{m}$ be the mass flow rate, A^* the throat area, L the channel length and B_0 the initial magnetic field, and define nondimensional density, pressure, enthalpy, velocity, magnetic and electric fields, current, area, and distance, by

$$\bar{\rho} = \left(\frac{A^*}{\dot{m}}\right)^2 \frac{B_0^2}{2\mu_0}\,\rho \qquad \bar{p} = \frac{2\mu_0}{B_0^2}\,p \qquad \bar{h} = \left(\frac{2\mu_0\,\dot{m}}{A^* B_0^2}\right)^2 h$$

$$\bar{u} = \frac{\dot{m}}{A^*}\frac{2\mu_0}{B_0^2}\,u \qquad \bar{E} = \frac{\dot{m}}{A^*}\frac{2\mu_0}{B_0^2}\,E_y \qquad b = \frac{B_z}{B_0} \qquad J = \frac{\mu_0 L}{B_0}\,j$$

$$a = \frac{A}{A^*}, \qquad \xi = \frac{x}{L}$$

Then we obtain

$$\bar{\rho}\,\bar{u}\,a = 1 \tag{1}$$

$$\bar{\rho}\,\bar{u}\,\frac{d\bar{u}}{d\xi} + \frac{d}{d\xi}\left(\bar{p} + b^2\right) = 0 \tag{2}$$

$$\bar{\rho}\,\bar{u}\,\frac{d\bar{h}}{d\xi} - \bar{u}\,\frac{d\bar{p}}{d\xi} = 2\epsilon J^2\,; \quad \bar{h} = \bar{h}(\bar{p},\ \bar{\rho}) \tag{3}$$

$$\epsilon J = \bar{E} - \bar{u}b \tag{4}$$

$$J = -\frac{db}{d\xi} \tag{5}$$

$$\frac{d\bar{E}}{d\xi} = -\,\bar{u}b\,\frac{d\,\ell n\,a}{d\xi} \tag{6}$$

Where the parameter ϵ is the inverse of the magnetic Reynolds number

$$\frac{1}{\epsilon} = \frac{\sigma L A^* B_0^2}{2\dot{m}} \tag{7}$$

Numerically, $\epsilon \sim 0.1 - 0.3$ for realistic MPD thrusters. For small ϵ,

the above system becomes singular, indicating the potential for initial and final "layers" with rapid change of the properties (including current concentration). A formal expansion in powers of ϵ leads to an "outer" set of equations where (3) gets replaced by

$$\bar{\rho}^0 \bar{u}^0 \frac{d\bar{h}^0}{d\xi} - \bar{u}^0 \frac{d\bar{p}^0}{d\xi} = 0 \tag{8}$$

i.e., isentropic flow, and (4), (5) and (6) simplify to

$$\frac{d}{d\xi} (\bar{u}^0 b^0 a) = 0 \tag{9}$$

which, together with (1), indicates $b^0/\bar{\rho}^0$ = const.. This "outer" flow can then be reduced easily to ordinary nozzle flow with an equivalent "γ" value close to 2, but modified slightly by the $\bar{p}$ term in (2).

On the other hand, regions near the channel inlet and exit, where specific boundary conditions have to be met, constitute the "inner" regions, with thickness $\Delta\xi \sim \epsilon$. In these regions we can ignore area variation and obtain the classical integrals (e.g. King, 1981.)

$$\bar{E}_i = \bar{E}_0 = \text{const.} \tag{10}$$

$$\bar{\rho}_i \, \bar{u}_i \, a_0 = 1 \tag{11}$$

$$\bar{u}_i + a_0 (\bar{p}_i + b_i^2) = \bar{u}_0 + a_0 (\bar{p}_0 + 1) \tag{12}$$

$$\bar{h}_i + \frac{1}{2} \bar{u}_i^2 + 2a_0 \bar{E}_0 b_i = \bar{h}_{T_0} + 2a_0 \bar{E}_0 \tag{13}$$

together with

$$\frac{db}{d\eta} = -(\bar{E} - \bar{u}_1 b) \quad ; \quad \eta = \frac{\xi}{\epsilon} \tag{14}$$

Analysis of this inner set of equations shows that sonic passage, if it occurs, requires a special smoothness conditions, which for constant γ is $\bar{u}_s b_s = \frac{\gamma - 1}{\gamma} \bar{E}_0$. In addition, the requirement that inner and outer regions merge asymptotically gives a specific outer boundary condition for the inner variables, i.e., $\bar{u}_1 b_1 = \bar{E}_0$ (where "1" represents the overlap region). Given $\dot{m}$, A^*, B_0, $\bar{h}_{r_0}$ and L, a count of equations and unknown shows that in order to complete the initial region specification, a downstream boundary condition on the outer solution is also needed. This is furnished by the condition (which can be inferred from the outer set, Eqs. (1) - (6)) of magnetoacoustic flow at the throat (or throughout the length if it is a constant-area duct):

$$\bar{u}^0_* = \sqrt{\bar{c}^2_* + \frac{2 b^{0\,2}_*}{\rho^0_*}} \tag{15}$$

where $\bar{c}_*$ is the sonic speed ($\sqrt{\gamma \frac{\bar{P}}{\rho}}$ in a constant-γ model).

On the other hand, if a condition b = 0 is imposed at the channel exit, as a crude way of "bottling up" the fringe magnetic field, then no extra conditions need to be imposed on the outer solution, other than its smooth matching to the new inner solution, which leads to b = 0 through a second $\Delta\xi \sim \epsilon$ layer.

These equations, when solved together, give the first order (in ϵ)

solution for the remaining unspecified inlet condition ($\bar{\rho}_0$, for instance), the electric field $\bar{E}_0$ (and $\bar{E}(\xi)$ more generally), and other quantities of interest at, for instance, the sonic point, the end of the inlet high current layer, the magnetosonic throat, or the channel exit. We have obtained solutions for both, a constant-γ model, and an Argon ionization equilibrium model of the gas, and verified the two models against each other in low temperature cases. A sample of these results is shown in Table 1, corresponding to the specification

$$\frac{\dot{m}_{ARGON}}{A^*} = 0.50 \text{ kg/sec/m}^2 \qquad B_0 = 0.1 \text{ Tesla}$$

$$T_{TOT,0} = 400 \text{ K} \qquad \frac{A_0}{A^*} = 2$$

Location	b	$\bar{u}$	$\bar{\rho}$	$\bar{p}$	$\bar{E}$	Mach #	Mach-Alfven #
Inlet	1	0.0143	34.882	0.0443	0.2832	0.3114	0.0588
Sonic Point	0.9793	0.1157	4.3225	0.0347	0.2832	1	0.1711
Edge of inlet layer	0.9401	0.3012	1.6599	0.0171	0.2832	2.2987	0.2896
Throat	0.6527	0.8677	1.1525	0.0093	0.5664	7.4775	1
Exit (Infinite Expansion)	0	1.5073	0	0	0	∞	∞

TABLE 1. NONDIMENSIONAL QUANTITIES FOR CONV-DIV MPD CHANNEL

Several features of Table 1 are noteworthy:

a) The flow is sub-magnetosonic (but mostly supersonic) in the "chamber" part of the channel.

b) There is a weak current concentration at inlet (carrying 1 - 0.9401, or 6%, of the total current).

c) Because of this last feature, the actual Argon temperature in the chamber is only 3100 K, too low for equilibrium ionization. Non-equilibrium effects should be accounted for, but this result emphasizes the "off-loading" of the channel inlet area.

d) There is a drastic density drop through even this weak current layer. This will hamper efforts at straight numerical simulation.

e) The ratio $\bar{p}$ of pressure to magnetic pressure remains at a few percent or below throughout the flow.

For comparison, Table 2 shows the rusults for a non-contoured, constant-area channel with otherwise the same data. The entire channel (except for the inlet and exit "layers") is now magnetosonic. The inlet region carries (1 - 0.63), or 37% of the current, the rest being carried by the exit current concentration. The extra inlet dissipation raises the Argon channel temperature to 7660 K (2.3% ionization, τ_{eff} = 1.18) but it (and the exit concentration) lowers the efficiency, as shown in the exit nondimensional velocity of about 1.12 (1 from EM effects, 0.12 from electrothermal expansion), compared to 1.51 for the case in Table 1. In fact for the perfect expansion of Table 1, the thermal energy resulting from the inlet dissipation is fully recovered, and the thrust effeciency is unity; but even if we assume no recovery beyond the throat, an efficiency of 0.95 is calculated (ignoring, of

course, all transport losses). By comparison, the thrust efficiency of the constant-area channel is only 0.687. Note also the even more extreme density drop through the inlet layer in this case.

Location	b	u	ρ	p	E	Mach #	Mach/ Alfven #
Inlet	1	0.0147	115.00	0.1520	0.4576	0.187	0.0622
Sonic Point	0.9304	0.1786	5.598	0.1156	0.4576	1	0.3058
Channel	0.6274	0.7290	1.3717	0.360	0.4576	4.188	1
Exit Plane (B = 0)	0	1.1212	0.8919	0.0374	0.4576	5.238	5.238

TABLE 2. NONDIMENSIONAL QUANTITIES FOR CONSTANT AREA CHANNEL

More complete results and trends will be included in the full paper, including extension to higher order in inverse Magnetic Reynolds number and comparisons to straight numerical simulations. Work is also underway on the related issues of wall losses and non-equilibrium ionization effects. Two companion papers will present two-dimensional simulation effects obtained numerically, and experimental results on a pair (contoured-straight) of channels.

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APPENDIX 3

Two-Dimensional Numerical Simulation of MPD Flows

by

J. Marc Chanty, R.C. Myer and M. Martinez-Sanchez

MIT

This paper will present results of our on-going work on numerical modeling in two or three dimensions of the fluid and electrodynamic property distributions that occur in plasma accelerators. This numerical approach is an important supplement to experimental and analytical studies, both of which have limitations of their own; yet, application of numerical models to electric propulsion has lagged behind other fields, where such applications are now more or less routine. In part this is due to the inherent difficulty of the governing equations where fluid and electromagnetic fields must be allowed to interact strongly, with the result that several spatial and temporal scales occur, convective and diffusive effects of several types compete, and the classical subsonic-transonic-supersonic regimes of gasdynamics must be expanded due to the occurrence of characteristic wave speeds other than that of sound.

We have developed a two-dimensional axially symmetric model of an MPD thruster using a finite-volume discretization approach in order to accomodate the complex geometry, an example of which is shown in Fig. 1. An automatic grid-generation code has also been produced to help in this process. The conservation equations for a 1-fluid model of the

plasma, and the Maxwell's equations are satisfied in the steady state by balancing the appropriate fluxes into and out of each of the finite volumes. The equations are then linearized successively about the best current solution, and incremental corrections are calculated throughout the flow by solving a large set of linear equations, the coefficients for which form a banded-structure matrix that is updated after each linear solution. This Newton-Raphson iteration converges rapidly (less than 10 cycles), but requires a large amount of data storage (about 3 Mb for a 20 x 40 grid).

Stability of the numerical process requires satisfaction of several criteria similar to those known from ordinary CFD work, but a complete study of the stability problem for our more complicated case is still lacking. We find empirically that artificial damping terms must be introduced in the equations, the effect of which, unfortunately, is to smear the finer details and introduce important inaccuracies in the results. These effects tend to be reduced as the grid resolution increases, but so far we have been limited by our Micro Vax II capabilities; about an order of magnitude increase in these, with the attendant improvement in the results, is expected as we move into our new multi-processor computer.

Figs. 2 and 3 show results obtained for one test case. Gross instability prevented solution for 20 KA, apparently due to very low densities near the anode. Even at 10 KA, a 30% reduction in anode density can be seen in Fig. 2, with a strong density gradient on the cathode surface. The contours in Fig. 3 are those of the velocity

divided by the local magnetoacoustic speed, which theory indicates should take the place of the ordinary sound speed in high-interaction flows.

In parallel with this work, we are currently adapting the method of Flux-Corrected Transport (Ref. 1), which holds greater promise for fully three-dimensional capabilities when coupled with the new vector multiprocessor machine. Preliminary results of this work are expected to be available for presentation at the meeting.

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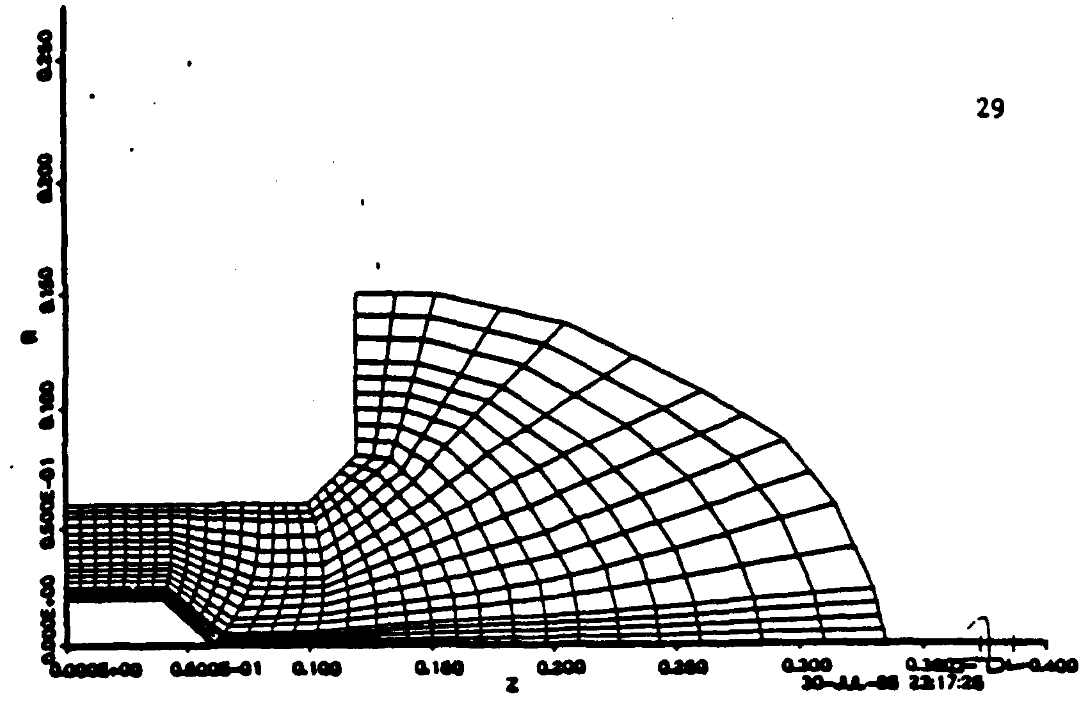

Fig. 1. Axysimmetric grid used for calculations

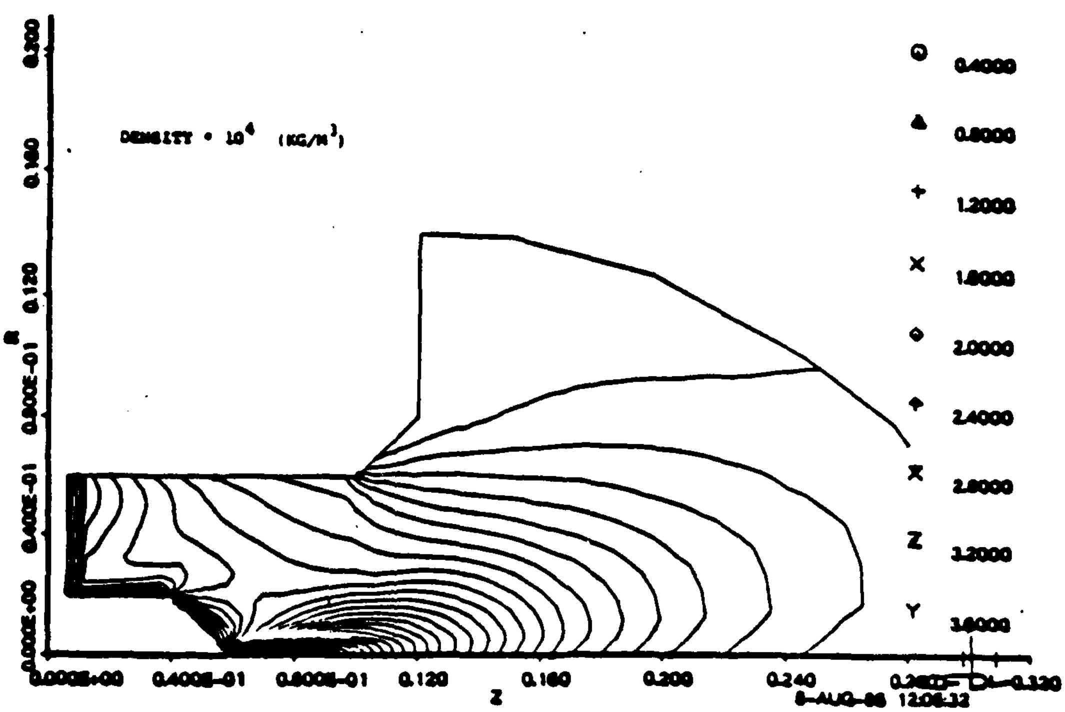

Fig. 2. Constant density contours for 6 g/sec of Argon, at 10 KA

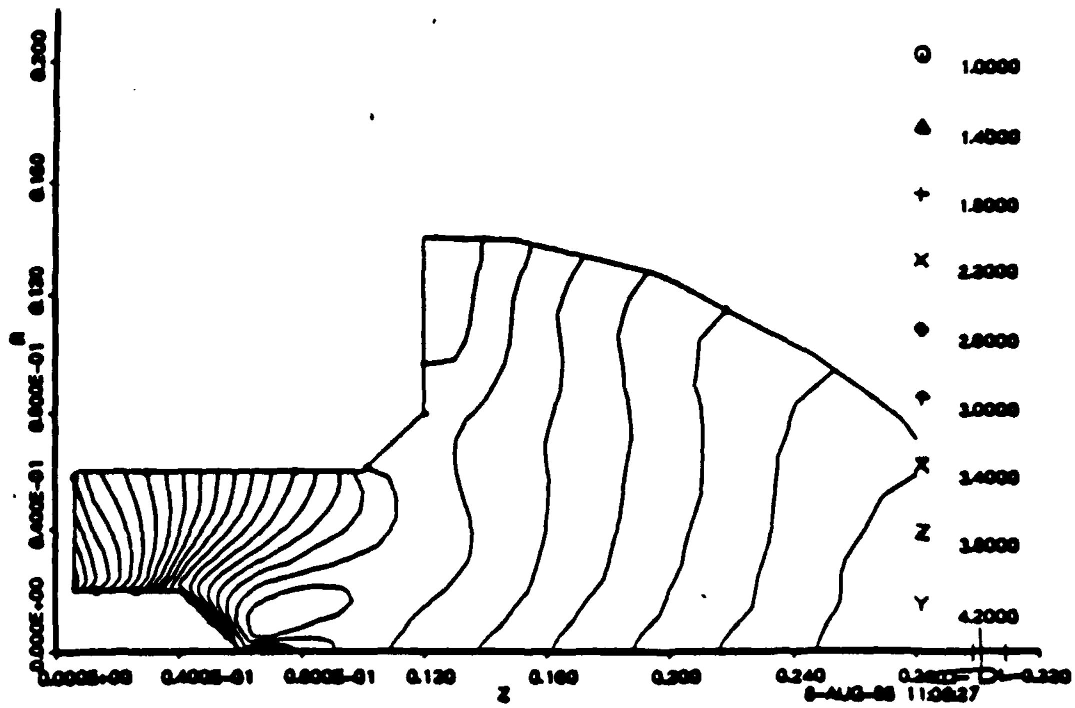

Fig. 3. Mach-Alfven contours for same case as Fig. 2

APPENDIX 4

PRELIMINARY DATA BASE

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Publication: AIAA Paper 73-1091, AIAA 10th Electric Propulsion Conference, Lake Tahoe, Nevada, Oct. 31-Nov. 2

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Author: Rudolph, L.K., Jahn, R.G., Clark, K.E., von Jaskowsky, W.F.
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Year: 1981
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Year: 1978
Laboratory: Princeton
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Title: Scaling of MPD Thrusters

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Author: Polk, J.E., von Jaskowsky, W., Kelly, A.J., Jahn, R.G.
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Year: 1985
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Year: 1979
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Laboratory: Space Power
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Year: 0
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Title: Efficiency and Onset in MPD Thrusters

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Year: 1985
Laboratory: MIT
Publication: AIAA Paper 85-2040, 18th International Electric Pr
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Author: Rock, B.A., Mantenieks, M.A., Parsons, M.L.
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Year: 1984
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